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The Economic Impacts of NIST's Software Error Compensation Research

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THE ECONOMIC IMPACTS OF NIST'S SOFTWARE ERROR COMPENSATION RESEARCH

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EXECUTIVE SUMMARY

The Manufacturing Engineering Laboratory (MEL) is one of the National Institute of Standards and Technology's (NIST's) eight major laboratories. A primary objective of MEL is the advancement of the state-of-the-art in manufactured parts measurement, dimensional metrology in particular. In the period between 1975 and 1985, discrete parts manufacturers worldwide were beginning to look at coordinate measurement machines (CMMs) as a cost effective way to increase the speed and accuracy of traditional measurement technologies. Increased measurement speed and accuracy, in turn, were an essential complement to the ongoing automation of production processes for manufactured goods and the drive for competitive position through lower cost and higher quality.

Software error compensation (SEC) is a computer-based mathematical technique for cost-effectively increasing the accuracy of CMMs and other machine tools. The focus of this economic impact assessment is the application of SEC technology to CMMs. When the MEL launched its SEC projects in 1975, the reigning technical approach to improved CMM accuracy was "error *avoidance*." As the competitive requirements for speed and accuracy of CMMs increased, the cost of the error avoidance approach rose geometrically. "Error *compensation*" on the other hand, embedded in the CMM's computer software, increased accuracy and enabled faster and relatively low-cost CMM designs to be produced.

Commercial introduction of software-compensated CMMs began in approximately 1985. When NIST began its SEC research, some ten years earlier, the software compensation approach was little understood. Because technical risks were high and market acceptance was uncertain, the prospects of recouping the necessary returns prevented commercial firms from making their investments in software compensation technology earlier. As a result, NIST's research reduced the eventual cost of commercial research and development efforts and accelerated the adoption and diffusion of SEC technology by CMM producers.

Between 1975 and 1985, NIST's total costs for SEC technology research were approximately $431,000.00. The research cost savings to CMM producers -- the first-level beneficiaries of NIST's research -- and the related efficiency gains in production were together approximately $93,600,000. Given the time distribution of the estimated benefits and costs, a first order approximation of the social rate of return from NIST's research leadership in SEC technology is 99 percent.

1. INTRODUCTION

The Manufacturing Engineering Laboratory (MEL) is one of eight research laboratories at NIST. Within MEL, there are four divisions: Precision Engineering, Automated Production Technology, Robot Systems, and Factory Automation Systems. One of the primary technical foci of the Precision Engineering Division is dimensional metrology.[1] An early outgrowth of that research in dimensional metrology at MEL was Software Error Compensation (SEC) technology. The purpose of this case study is to examine the first-order economic impacts associated with the development and initial diffusion of SEC technology to producers of coordinate measuring machines (CMMs).

In its attempt to support the global competitiveness of U.S. industry, MEL has long been part of the race to stay ahead of the trend toward increasing precision and accuracy. It has attempted to provide industry with state-of-the-art measurement tools in a timely manner. This is a critical contribution because all manufacturing industries are requiring products with increasingly complex shapes, and with features with increasingly smaller dimensional tolerances. One of MEL's goals has been to facilitate industrial adoption of strategically important manufacturing and computing hardware equipment and software standards, especially those related to the discrete-parts manufacturing sector. SEC technology is but one example.

SEC is a computer-based mathematical technique for cost-effectively increasing the accuracy of CMMs and other machine tools. The focus of this economic impact assessment is the application of SEC technology to CMMs. Because they combine quicker inspection with more accurate measurement, CMMs are supplanting more traditional manufacturing measurment equipment. The application of SEC technology to CMMs significantly accelerated their adoption by manufacturers.

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[1] Metrology is defined as the science of measurement. The specific issues of concern to the Precision Engineering Division are: dimensional metrology (the subject of this SEC technology case study), machine metrology, micro-metrology, microelectronics metrology, and surface and particle metrology.

Traditionally, increased precision could only be obtained through expensive changes in the design and construction of a CMM. With SEC, significant improvements in accuracy can be obtained by mathematically correcting the highly repeatable errors rooted in the machine's design and construction, thus avoiding the expense of overall design changes. While the economic impacts that have resulted from NIST's research in SEC technology have been significant, it is safe to project more substantial economic benefits in the future as this accuracy-enhancing technology diffuses throughout the manufacturing sector.

CMMs perform highly repeatable functions. In performing these functions, inaccuracies embedded in the manufacture and assembly of the CMM are repeated time after time. The solution to overcoming these embedded inaccuracies is either to manufacture a more accurate, and more expensive CMM, or to compensate for the embedded inaccuracies by systematically identifying and then programming them into what is known as an error compensation map. This error compensation map can be incorporated into software used to operate the CMM controller. In practice, as a CMM's probe begins to move to its position to measure the designated device, the controller will refer to the error compensation map to make the necessary correction to the dimensional accuracy calculations it presents to the CMM user.

The introduction of SEC in the mid- to late-1980s "revolutionized" the domestic CMM industry and simultaneously strengthened the international competitive position of U.S. manufacturers.[2] In addition to increasing the speed and accuracy of industrial measurement for users of compensated CMMs, SEC technology has broadly enhanced the ability of manufacturers employing CMM technology to compete on the basis of greater overall production speed and higher product quality. And, as SEC technology continues to diffuse, its impact on the machine tool industry is expected to be greater yet.[3] In other words, the first-order economic impacts of NIST's SEC development efforts presented in this case study likely represent only a partial picture of the eventual economic impacts to be realized from this NIST research.

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[2] The revolutionary impact of SEC technology was the theme of numerous interviews with industry and technology experts. See also, John A. Bosch (ed.) *Coordinate Measuring Machines and Systems,* (Marcel Dekker) 1995; and "Design Case Study: A Coordinate Measuring Machine," in A.H. Slocum, *Precision Machine Design,* (Prentice-Hall) 1992, pp. 45-57.

In the mid- to late-1980s, SEC technology became nearly universally adopted by CMM manufacturers world-wide as a cost-effective means to improve the accuracy of CMMs. For U.S.-based CMM manufacturers, NIST played a very important role in the early development, demonstration, and diffusion of SEC technology. Regarding the economic impact of NIST's efforts, we conclude that NIST's total research costs for SEC technology research between 1975 and 1985 were approximately $431,000.00. The research cost savings to CMM producers -- the first-level beneficiaries of NIST's research -- and the related efficiency gains in production were together approximately $93,600,000. Given the time distribution of the estimated benefits and costs, a first-order approximation of the social rate of return from NIST's research leadership in SEC technology is 99 percent.

In the following sections of this report we:

- Place the development of dimensional metrology in an historical context
- Introduce the reader to CMMs and the CMM market
- Explain SEC technology, as it applies to CMMs
- Characterize NIST's unique contribution to the development of SEC technology
- Trace the diffusion of SEC technology throughout the CMM industry
- Present an approach to quantifying the first-order economic impacts attributable to SEC technology
- Estimate the first-order economic impacts associated with NIST's research on SEC technology.

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[3] Jun Ni, "Coordinate Measuring Machines," in John A. Bosch (ed.) *Coordinate Measuring Machines and Systems*, p. 40 (draft manuscript) 1994.

2. HISTORICAL BACKGROUND

The technology of manufacturing accuracy has deep roots in American economic history. In the mid-19th century, British observers commented on a uniquely American approach to manufacturing, an approach often referred to as the “American System of Manufacturing."[1] The essence of the "American System" was the standardization and interchangeability of manufactured items. This approach to manufacturing was fundamentally different from the English approach, which stressed labor-intensive customization by highly skilled craftsmen.

Interchangeability presumed manufacturing precision, and thus interchangeability greatly reduced the very costly stage of fitting activities by moving toward a simpler assembly process that required "nothing but a turnscrew (screwdriver)." Interchangeable components, the elimination of dependence upon handicraft skills, and the abolition of extensive fitting operations were all aspects of a manufacturing system whose fundamental characteristic was the design and utilization of highly specialized machinery.

The evolution of specialized machines brought about by the emphasis on interchangeability was abetted by the evolution of the technology of measurement. And, as cheaper and more effective measurement devices became available, not only did the degree of interchangeability achieved on manufacturing machines increase, but also the production of the specialized machinery itself became a specialized activity undertaken by a well-defined group of firms in the manufacturing sector.[2] The development and use of measurement technologies is an important part of that history. The CMM, in turn, is in many respects the culmination of the development of dimensional measurement technology.

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1 Nathan Rosenberg, *Technology and American Economic Growth*, (Sharp, New York) 1972, pp. 91-116.

2 Rosenberg, *Op. Cit*., p. 95

The concept of interchangeable parts necessitated the creation of the concept of part tolerance.[3] And the ability to produce large numbers of parts of sufficiently small variation is based on the ability to measure such variation accurately. Today, the objectives of interchangeability and part tolerance have become increasingly more demanding, with a trend toward steadily decreasing tolerances. The development of SEC technology at NIST was, in large part, a response to the metrological demands of discrete part manufacturers for ever-increasing manufacturing accuracy and precision.

The CMM, and its associated SEC technology, are part of a so-called "second industrial revolution" that first became evident in the 1960s. This revolution was based on the application of science to industrial processes and the development of unified systems of automated industrial control.[4] Clearly, NIST's development of SEC technology is part of this historical process. In fact, informed observers suggest that the application benefits of SEC technology go well beyond CMMs to a variety of cutting and forming machine tools and these broader benefits have only begun to be realized.

2.1 THE MARKET FOR COORDINATE MEASURING MACHINES

2.1.1 The Evolution of Dimensional Measurement Technology

CMMs are the culmination of the technological evolution of dimensional measurement and integrally related to the evolution of manufacturing technology.[5] Measurement technology is so much a part of modern industrial life that it is taken for granted by the general consuming public. It is an ever-present reality for discrete part manufacturers. The conformance of manufactured parts to increasingly precise specifications is fundamental to U.S. manufacturers remaining competitive in the world market. While a detailed review of the evolution of dimensional

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3 Steven Phillips, et al., *Measurement Uncertainty Considerations for Coordinate Measurement Machines,* (NISTIR # 5170), April 1993, p. 1.

4 Robert Robertson and Gary Walton, *History of the American Economy,* (Harcourt Brace Jovanovich, New York) 4th edition, 1979, pp. 447-453

5 "CMMs are the most truly modern method of dimensional inspection." C. Kennedy, et al., *Inspection and Gaging,* (Industrial Press Inc.) 6th edition, 1987. p. 576.

measurement technology is well beyond the scope of this report, rudimentary familiarity with basic industrial measurement devices is helpful to understanding the significance of CMMs and, in particular, the introduction and application of SEC technology.

A wide variety of gaging and measuring devices are employed in a contemporary manufacturing environment, including: probes; rules; squares; calipers; micrometers; all manner of gages (for assessing the accuracy of bore, centering, chamfer, force, height, strain, and thickness just to name a few performance dimensions); gage blocks; automatic sorting systems; lasers; optical and mechanical comparators; flatness testers; interferometers; and, of course, coordinate measuring machines.[6] The functions performed flexibly, quickly, and accurately by a CMM have historically been performed with some combination of the types of individual mechanical measuring devices just mentioned.

Perhaps the most basic measuring device is the ruler; a standard of length. The steel rule (sometimes referred to as a "scale") remains the primary factory measuring tool today.[7] The choice of measurement tool depends on the sensitivity and resolution required. A common commercial variation of the steel rule is the combination square. In addition to its use for direct linear measurement, the combination square is used to assess angles and depths. Calipers and micrometers are also traditional measurement devices for assessing dimensional accuracy. They are generally used in combination with, or as an accessory to, the steel rule especially in the measurement of diameter and thickness. The first practical mechanic's micrometer was marketed in the United States in 1867 by Brown & Sharpe.[8]

Precision gage blocks are another common measurement technology. Commercial gage blocks are steel blocks, hardened with carefully machined parallel and flat surfaces. They are used to build-up various gaging lengths. (For example, by joining a 1-inch block to a 2-inch block 3

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6 This list of measuring devices is taken from, *Quality Magazine*, "Brand Preference and Market Potential Survey: Dimensional Gaging Equipment, 1993."

7 C. Kennedy, et al., *Inspection and Gaging*, (Industrial Press Inc.) 6th edition, 1987.

8 John A. Bosch (ed.) *Coordinate Measuring Machines and Systems*, (Marcel Dekker) 1995, pp. 4-6.

inches in length are obtained.) Great care is taken in the manufacturing of these devices to ensure flat, parallel measuring surfaces. The gage blocks are graded for various levels of accuracy. Common grading recognizes “master blocks” (highest accuracy), “inspection blocks,” and “working blocks” (lowest accuracy).

Another “measurement building block” is the surface plate. A surface plate is a truly flat, level plane. It may be made of caste iron, granite, or glass block; set level on a bench, stand, or table with its one flat, polished surface facing upward. Conceptually, a surface plate provides the X-axis in a measurement set-up.

The “comparator” combines any number of the above measurement instruments in a test set-up that allows the comparison of unknown with known dimensions. For complex parts, that need to be measured in three dimensions, the comparator consists of instruments which, integrated as a single measuring set-up, constitute X, Y, and Z measurement axes. The basic comparator consists of a surface plate or flat surface (the horizontal “X” coordinate), a test set or fixture (the vertical “Y” coordinate), and an indicator (typically attached to the “Z” arm of the test set-up).[9]

2.1.2 What is a Coordinate Measuring Machine (CMM)?[10]

In one respect, CMMs are just a refinement of the gaging and measuring equipment discussed above. CMMs combine many of the features of traditional measuring devices into one integrated, multi-functional measuring machine. In other respects, they are a major breakthrough in mechanizing the inspection process and in lowering its cost.[11] CMMs provide three-dimensional measurements of the actual shape of a work piece; its comparison with the desired shape; and the evaluation of metrological information such as size, form, location, and orientation. As a means of

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[9] A number of indicator technologies (pressure, air, optical, electronic) are used to translate the physical interaction of the testing equipment and the part being measured. These indicator devices provide the measurement *data* -- the “readings” -- to the measurement technician.

[10] This section draws heavily from John A. Bosch (ed.) *Coordinate Measuring Machines and Systems,* (Marcel Dekker) 1995.

[11] C. Kennedy, et al., *Inspection and Gaging,* (Industrial Press Inc.) 6th edition, 1987, p.575.

measuring the dimensional quality of manufactured items, CMMs are accurate, fast, flexible, and versatile.

The automation of machine tools in the 1950s and 1960s created the need for a faster and more flexible means of measuring manufactured parts. Parts made in a matter of minutes on the then new numerically-controlled machines took hours to inspect. This inspection requirement resulted in a new industry of three-dimensional measuring machines. In more recent times, the emphasis on statistical process control for quality improvement has accelerated the demand for faster and more accurate measurements.

The "power" of CMMs is derived from their ability to compute, from the measured points in three-dimensional space, any one of a whole family of dimensional quantities such as: position of features relative to part coordinates; distance between features; forms of features, such as flatness, circularity, and cylindricity; and angular relationships between features, such as perpendicularity.

The five basic CMM design configurations, shown in Table 2.1-1, are moving bridge, fixed bridge, cantilever, horizontal arm, and gantry. The configuration of the CMM is selected on the basis of the measurement precision required and the size and complexity of the work piece to be measured.[12]

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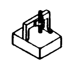
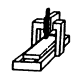
[12] "Taking the Measure of CMMs," *American Machinist*, Special Report 749, October 1982, pp. 145-160.

Table 2.1-1 Common CMM Configurations and Their General Use[13]

Configuration / Applications	Moving Bridge	Fixed Bridge	Cantilever	Horizontal Arm	Gantry
					
General Purpose	X	X	X	X	
Precision	X	X (gauge calibration)			
Large Parts			X	X (car bodies, diesel engine blocks)	X (aerospace structures, large vehicles)

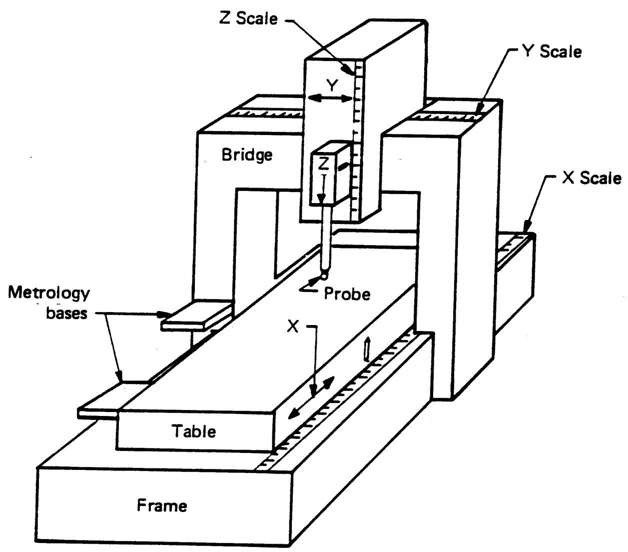


Figure 2.1-1 The Fixed-bridge CMM Configuration[14]

The essential feature of the CMM is its three carriages, or “guideways.” These are noted as the X scale, Y scale, and Z scale in Figure 2.1-1. These three carriages form a three dimensional

[13] Source: John A. Bosch (ed.) *Coordinate Measuring Machines and Systems,* (Marcel Dekker) 1995, p. 45

[14] Source: Robert J. Hocken, *Machine Tool Accuracy,* (Volume 5 of *Technology of Machine Tools*) Lawrence Livermore Laboratory, Report # UCRL-52960-5, October 1980, p. 19.

coordinate system, reference to which is the basis for the measurement of a work piece in three dimensional space. The object to be measured ("work piece") is fixed to the work table and a coordinate frame of reference is established. In accordance with a measurement plan, the touch probe makes numerous contacts with the work piece and sends this actual dimensional information to the CMM computers for processing and display.

2.1.3 The Economic Role of CMMs

From a strategic business perspective, the ultimate economic value of the CMM is derived from its flexibility and ability to execute production process control. Quality is identified as a key strategic imperative for many manufacturers, and process control is at the heart of quality assurance. CMMs can provide such control cost-effectively. Table 2.1-2 summarizes many of the advantages of CMMs over more conventional approaches to measurement.

Table 2.1-2 Comparison of Conventional and Coordinate Measuring Procedures[15]

Conventional Metrology	Coordinate Metrology
Manual, time-consuming alignment of the test piece	Alignment of test piece is not necessary
Single-purpose and multi-point measuring instruments make it hard to adapt to changing measuring tasks	Simple adaptation to the measuring tasks by software
Comparison of measurement with standard measurement fixtures is required	Comparison of measurements with mathematical or numerical models
Different machines required to perform determinations of size, form, location and orientation	Determination of size, form, location, orientation in one setup using one reference system

The following excerpt provides a clear explanation of the source of the economic value provided by CMMs relative to traditional approaches to measurement:

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15 Source: John A. Bosch (ed.) *Coordinate Measuring Machines and Systems*, (Marcel Dekker) 1995, p. 44

> Let us take a specific example to see why an inspection department is prompted to install a coordinate measuring machine rather than rely on conventional surface plate inspection methods. In this typical case, a bottleneck occurs when inspection is confronted with the necessity of measuring 12 hole locations in 50 machined castings where 100% inspection is required. The tolerances are plus or minus .001 inch for location of the holes relative to their reference points on X and Y coordinates. The holes are also related to an edge to very close tolerances. The inspector quite naturally turns to his surface plate, a precision knee, a stack of gage blocks and a height gage.... Now because the basic surface plate technique [requires that the work piece is perpendicular to the surface plate], there must be one setup of the part to measure the holes in one direction (the X direction), and another setup to measure the holes in the Y direction. The surface-plate technique is time consuming and tedious.... The amount of time spent on measuring the hole locations in each of these castings might very well average 2 hrs., and the time to measure the batch of 50 parts would then be 100 hrs. No wonder the chief inspector looks for another faster solution to this problem.
>
> Now lets take the same measurement job of 100% inspection and instead of using the conventional surface plate technique apply a coordinate measuring machine to the problem.... After the part is staged on the table, the tapered probe of the machine is inserted into each hole in turn with the X and Y coordinates read directly from the continuous travel dial indicator. Both readings are obtained at each setting. The time to measure the dimensions of the 12 holes in both directions should not take more than 15 to 20 minutes including the time to set the piece up on the table and establish the datum reference. In this case the time saved using the CMM as opposed to conventional inspection methods amounts to more than one and one half hours per part. *What is demonstrated by this example is the prime advantage of the coordinate measuring machine which is quicker inspection coupled with accurate measurements*. [Emphasis added][16]

Table 2.1-3 shows the relative frequency with which CMMs are used in various manufacturing functions. As indicated, CMMs are most frequently used for quality control and shop floor production inspection.

[16] C. Kennedy, et al., *Inspection and Gaging,* (Industrial Press Inc.) 6th edition, 1987, pp. 575-576.

Table 2.1-3 Functional Applications of CMMs[17]

Functions	Frequency of Use
Quality Control Department	30%
Shop Floor/Production Inspection	24%
Tooling	17%
Receiving Inspection	17%
Metrology Laboratory	10%

As shown in Table 2.1-4, CMMs are used throughout the manufacturing sector by large and small firms, and this use has increased in nearly every industry between 1984 and 1989. The data in Table 2.1-5 indicate that CMMs are also used in organizations of all sizes.

Table 2.1-4 CMM Use by SIC: 1984 vs. 1989[18]

Industry	Number of CMMs/(% of Total): 1984	Number of CMMs/(% of Total): 1989
SIC 25: Furniture & Fixtures	0	43 (<1%)
SIC 33: Primary Metal Industries[19]	303 (4%)	31 (<1%)
SIC 34: Fabricated Metal Products	780 (12%)	1,075 (7%)
SIC 35: Industrial Machinery & Equipment	3,028 (46%)	6,718 (43%)
SIC 36: Electronic & Other Electric Equipment	900 (14%)	2,825 (18%)
SIC 37: Transportation Equipment	1,067 (16%)	4,659 (30%)
SIC 38: Instruments & Related Products	412 (6%)	398 (3%)
SIC 39: Misc. Manufacturing	91 (1%)	19 (<1%)
Total CMMs	6,600 (100%)	15,678 (100%)

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17 Source: *Production Magazine*, "A Benchmark Study About Coordinate Measuring Machines," 1993. The question posed in the survey is as follows: *"What is the application for CMM's at your facility? (Check all that apply)"*

18 The data presented in this table represent numbers of CMM machines and percents of the estimated total CMM inventory in U.S. industry. Data are derived from surveys conducted by *American Machinist* in 1984 and 1989. An update of machine tool inventory is planned for late 1996. The question posed to respondents was*: "How many [CMM] machines do you have at your plant?"* The population surveyed in 1989 was the subscription list of the *American Machinist* magazine. This represents some 40,000 manufacturing firms. The number of subscribers in 1984 is unknown. In 1996, *American Machinist* subscribers number some 48,000.

19 The drop in the number of CMMs between 1984 and 1989 for SICs 33 and 39 cannot be explained. The *American Machinist* was purchased by Penton Publishing in 1989 and no records are available concerning the methodology for the 1984 survey. (Personal communication with Ray Herzog, Director of Research, Penton Publishing, March 1996.)

Table 2.1-5 Distribution of CMMs by Plant Size: 1989[20]

Plant Size (Employees)	Number of CMMs/ (% of Total)
1-19	1,801 (11%)
21-99	5,894 (38%)
100-499	4,018 (25%)
500+	4,055 (26%)
All Plants	15,678 (100%)

In summary, CMMs are powerful measurement instruments capable of cost-effectively measuring manufactured items in a wide and growing range of manufacturing applications.[21]

2.1.4 Evolution of the CMM Industry

The development of the CMM is inextricably linked to the development of automated machine tools.[22] In fact, the first CMM was developed by Ferranti, Ltd., between 1956-1962, as a companion product to its growing family of numerically-controlled (NC) machine tools. Ferranti had not been in the measuring equipment business, but developed the CMM in response to perceived market need for faster and more flexible measuring when machining became more automated. Parts made in a matter of minutes on the new NC machines took hours to inspect. In 1956, Harry Ogden, the designer of Ferranti's CMM, conceived a measuring machine that would fundamentally change the economics of conventional inspection methods by reducing inspection time and the skill required for inspection. The demand for the Ferranti machine, and its successors, created a large market throughout the industrial world and led to the development of similar machines with larger capacities and improved accuracy and resolution.

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[20] Because the 1984 *American Machinist* inventory did not collect data on individual machines by plant size, no comparison with 1989 data could be made. (Personal communication with Ray Herzog, Research Director, Penton Publishing, March 1996)

[21] While CMMs may be the epitome of measurment technology from a technical perspective, cost-effectiveness considerations ultimately determine the choice of production technology. So, despite the growing acceptance of the utility, flexibility, and sophistication of CMMs relative to the traditional measurement technologies, they are an *appropriate measurment technology* for manufacturing situations in which manufactured items have multiple features and relatively high unit costs, production runs are relatively short, one part must be inspected and passed before machining on the next part can start, and manufacturing flexibility is required. See, Ted Busch, *Fundamentals of Dimensional Metrology,* 2nd edition, (Delmar) 1989, pp. 527-528.

Inspired by the Ferranti CMM displayed at the 1959 International Machine Tool Show in Paris, the Sheffield Division of Bendix Corporation displayed its first CMM in 1960. Soon thereafter, Bendix's customer, Western Electric, had compared conventional measurement times to the measurement times of the Bendix CMM, and found a 20-fold increase in measurement speeds. These were the kinds of savings that drove the demand for CMMs worldwide. After this, competitors entered this growing world market at an average rate of two per year for the next 25 years.

In 1962, the Italian company, Digital Electronics Automation (DEA) became the first company established for the purpose of manufacturing CMMs. DEA delivered its first machine in 1965. Over the next thirty years, DEA would grow to one of the top suppliers of CMMs worldwide. Two world-renowned "old-line" machine tool manufacturers entered the growing worldwide market for CMMs in the early 1970s. Brown & Sharpe entered the CMM market in 1972**.** Zeiss delivered its first CMM in 1973. The Japanese firm, Mititoyo, began development of CMMs in 1968 and its CMMs were commercialized in 1978. In 1989, Zeiss acquired the U.S. CMM producer Numerex (Numerex sold its first CMM in 1978) and Giddings & Lewis acquired Sheffield. In 1992, the original designer of CMMs, Ferranti, ceased production of CMMs. In 1994 Brown & Sharpe acquired DEA. Today, standard industry assessments identify some 25-30 CMM manufacturers worldwide but only a handful are estimated to have market shares exceeding 5 percent.[23] Table 2.1-6 provides information concerning key events in the evolution of the worldwide CMM industry.

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[22] Unless otherwise cited, this section draws heavily from John A. Bosch (ed.) *Coordinate Measuring Machines and Systems,* (Marcel Dekker) 1995, and from interviews with industry representatives.

23 The standard survey sources are as follows: *Production Magazine,* "A Benchmark Study About Coordinate Measuring Machines," 1993; and *Quality Magazine,* "Brand Preference and Market Potential Survey: Dimensional Gaging Equipment, 1993."

Table 2.1-6 Key Events in the Evolution of the Worldwide CMM Industry

CMM Producer	Delivered First CMM	Comments
Ferranti (Italy)	1959	Exited the CMM market in 1992
Sheffield/Giddings & Lewis (U.S.)	1960	Sheffield merged with G&L in 1989
Digital Electronics Automation (Italy)	1965	Merged with Brown & Sharpe in 1994
Brown & Sharpe (U.S.)	1972	Acquired DEA in 1994
Zeiss	1973	Acquired Numerex in 1989
Mititoyo (Japan)	1970	
Numerex (U.S.)	1978	
Starrett (U.S.)	1982	
		Merged with Zeiss in 1989

During interviews conducted as part of this study, industry experts estimated that the leading firms internationally, Brown & Sharpe and Giddings & Lewis, together command greater than 50 percent of a $500 million (1995) world market for CMMs. The domestic market is approximately $250 million. Table 2.1-7 provides an estimate of each dominant CMM producer's current world market share.

Table 2.1-7 Dominant Firm Worldwide Market Share Estimates, 1995[24]

Company	Market Share
Brown & Sharpe (w/DEA)	45%
Giddings & Lewis (Sheffield)	17.5%
Zeiss (w/Numerex)	17.5%
Mitutoyo	15.5%
Starrett	9%

[24] These market share estimates are based on information provided in interviews with industry experts and brand preference surveys identified in footnote 25. Shares do not add to 100 percent due to rounding and because the preference ranking reports cited at footnote 25 allowed respondents to select multiple firms. These estimates assume that the worldwide market is split only among the five dominant firms. In fact, there are numerous fringe firms with small or specialty niche market shares.

3. THE DEVELOPMENT OF SOFTWARE ERROR COMPENSATION TECHNOLOGY

3.1 THE COMPETITIVE ENVIRONMENT

The CMM industry has followed the path of many developing, yet technologically sophisticated, industries. Its brief history is one of continuous entry and consolidation. In large part, the development of this industry has been driven by the pace of complementary technological development in other industries -- most notably the computer and machine tool industries. In addition to its organic connection to these industries, the CMM industry has also been driven by the global emphasis on higher quality in all areas of manufacturing. In many ways, the metrology industry, of which CMMs are an important part, is a rate-determining factor in the quest for quality, precision, and speed because measurement is the sufficient condition for effecting manufacturing process improvement.

For some manufacturers, precision is extremely important and demands for increasing precision are a dominant competitive force. For continued competitiveness in the global market, the ability to manufacture to increasingly tight dimensional tolerances is imperative. As evidenced by Japan's success in automobiles, machine tools, video recorders, microelectronics devices, and other super-precision products, improvements in dimensional tolerance and product quality are a major factor in achieving dominance of markets.[1]

For example, critical dimensions for manufacturers of automobile engine blocks, include length, width and height; the location of the oil pan and its holes; the diameter, orientation, and surface roughness of its cylinder bores. Microelectronics wafers provide another example. Critical

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[1] For an empirical demonstration of trends in manufacturing tolerances see, Dennis Swyt, *Challenges to NIST in Dimensional Metrology: The Impact of Tightening Tolerances in the U.S. Discrete-Part Manufacturing Industry*, (NIST Report # NISTIR-4757) January 1992; and *Issues, Concepts, and Standard Techniques in Assessing Accuracy of Coordinate Measuring Machines*, (NIST Technical Note 1400) February 1993.

dimensional characteristics include wafer diameter, thickness, flatness and roughness; the linewidth, spacing, and positioning of multiple layers; and the number and size of the particles on the wafer that can produce defects. The ability to measure these features and to ensure that underlying manufacturing processes are under control (and, therefore, that they can reliably produce quality products) is increasingly seen as the essence of sustainable competitive advantage for many manufacturers.[2]

3.2 WHAT IS SOFTWARE ERROR COMPENSATION (SEC)?[3]

The purpose of a CMM is to assess accuracy measured to, for example, one ten-thousandths of an inch. SEC technology is a computer-based mathematical technique for increasing the accuracy of CMMs and increasingly, cutting and forming machine tools. SEC technology, embedded in a CMM's controller's software, embodies four essential elements:[4]

- Knowledge of error sources in the automated measuring process
- A mathematical model of the CMM
- A methodology of measurement to supply data to the model
- A methodology for implementing the model in the CMM analysis computer.

While a detailed discussion of each of these elements is beyond the scope of this study, a brief discussion of error sources is important for understanding the fundamental problem that SEC technology addresses.

Consumers often take accuracy for granted and simply refer to objects as flat, smooth, straight, round, parallel, or square. However, for manufacturers, the degree of flatness,

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2 Gregory Tassey, *Technology Infrastructure and Competitive Position,* (Kluwer) 1992; National Center for Manufacturing Sciences (NCMS), *Competing In World-Class Manufacturing,* (Business One Irwin) 1990; and Albert Link and Gregory Tassey, *Strategies for Technology-based Competition,* (Lexington Books) 1987.

3 SEC is applicable to both machine tools and measuring machines. With few exceptions, to date, its commercial implementation as been largely restricted to CMMs. This investigation is limited to CMM applications.

4 Robert J. Hocken, "Software Correction of Precision Machines," (Draft) July 1993

straightness, or roundness, is an aspect of the quality of the product. SEC technology addresses what metrologists call quasistatic errors of relative position between the CMM probe and the work piece. (The probe is the part of the CMM that contacts the object being measured to establish its true position and dimensions.) The position of both the probe and the work piece vary slowly in time and are related to the structure of the CMM itself.[5] All three variables combine to create a difficult measurement problem.

There are three types of quasistatic errors: geometric (or volumetric) errors, thermally-induced errors, and load-induced errors. As the X, Y, or Z carriages move along their respective scales (refer back to Figure 2.1-1), they are subject to six types of geometric error -- three "angular errors" (yaw, pitch, and roll) and three "straightness errors" (left or right of straight, up and down with respect to center, and too far or short of nominal length). In addition, the X, Y, and Z scales should theoretically be perpendicular to each other, adding three more potential sources of geometric measurement error, for a total of 21 possible geometric error sources.[6]

In addition to geometric errors, CMM are also subject to thermal errors. That is, as machine parts warm and cool, the materials with which they are made expand and contract. There are multiple sources of thermally induced errors including: room environment (temperature and lighting), heat created by the machine (friction, electrical and electronic devices, and hydraulic systems), and heat generated by individuals in the work environment.

A final source of error is related to "load effects." CMMs are subject to a variety of loads that cause deformation of the machine itself. These load effects include stresses resulting from the mounting of the machine to the floor or base, stresses resulting from the dead weight of the machine components, and stresses resulting from work piece weights. While technology developments at NIST and throughout the CMM industry have continued to address thermal and

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[5] Robert J. Hocken, *Machine Tool Accuracy*, (Volume 5 of *Technology of Machine Tools*) Lawrence Livermore Laboratory, Report # UCRL-52960-5, October 1980, pp. 8-26.

[6] Robert J. Hocken, "Software Correction of Precision Machines," NIST Contract # NIST- 60NANB2D1214, (Draft) July 1993, pp. 3-6

load effect errors, this report focuses on the economic impact of NIST’s original research addressing *geometric* errors.

3.3 THE TECHNICAL SIGNIFICANCE OF SEC

The SEC concept revolutionized the traditional approach to improving the accuracy of CMM and other precision machines. Metrology experts distinguish two broad error-reduction strategies: error avoidance and error compensation. Error avoidance seeks to eliminate the source of the error through greater precision in the manufacture of machine parts. Error compensation seeks to cancel the effect of the error without eliminating its source.

Historically, error compensation was achieved by adding mechanical devices to a machine. For example, throughout the 19th century machine tool users rotated a lead screw to move a nut (which carries a cutting tool) along a set of "ways" (a track or slide on the machine tool). By rotating the leadscrew, the nut moved along a linear path by an amount related to the number of threads on the leadscrew. If the leadscrew had 12 threads per inch, one revolution would advance the nut 1/12 inch (0.083). If, because of an error in manufacturing, the leadscrew had 12.2 threads per inch, one rotation of the screw would advance the nut by somewhat less than 1/12 inch (0.082). This error would then be reproduced on the work piece. Traditionally, this error in the leadscrew was compensated for by a device that rotated the nut (rather than the leadscrew) by an additional amount according to defects of the leadscrew. Of course, in the nineteenth century, hardware was the only method available to store the leadscrew error information. Today, the error information would be stored in software as part of computer memory.

According to CMM technology experts, the historical problem of the lead screw error in a simple machine tool is greatly compounded in today’s expensive three-dimensional CMMs:

> Compensating for a deforming machine structure represents a complex problem. On a small or simple machine, it often can happen that one of the many geometrical deficiencies dominates the total error.... [T]he magnitude of the error often has a simple approximation.... On larger machines, the error matrix in three dimensional space can be very difficult to establish, especially if high accuracy is sought. Even if the values of errors are established, it is far from simple to utilize such information

in storage to effect multidimensional coordinate transformations at the very high speeds necessary.... The enormous escalation of difficulty in going from two- to three-dimensional space is a limitation often not appreciated. In fact, it represents one of the major challenges to machine tool metrology.

A second limitation stems from the basic [and incorrect] philosophy of "the smaller the error, the easier the compensation." The effort involved in software correction grows exponentially with the fraction to which it has been reduced. A rule of thumb is that 10% is easy, 1% is attainable with effort, and 0.1% requires a major and expensive attack.... Thus, the errors that motivate compensation and the limitations to compensation are similar.[7]

From the perspective of economics, as precision tolerances have become less and less forgiving, the investment cost of error *avoidance* strategies has risen accordingly. This fundamental reality is the basis for the appeal and acceptance of error *compensation*. For the same level of investment, CMMs are usually much more accurate than the machine tools whose outputs they measure. Machine tools have to contend with significant amounts of heat (from their motors and from the cutting process), large amounts of vibration, substantial cutting forces, and other factors that degrade their accuracy. These factors are either absent or greatly reduced in CMMs. So, the increased costs of ever higher accuracy measurements may be more than offset by the reduced scrap rate savings made possible by more accurate measurement.[8] The same logic applies equally to the manufacture of CMMs themselves and when NIST launched its SEC development projects, the error *avoidance* approach to CMM design and construction was dominant.[9] The introduction of software error *compensation* allowed fundamental changes in the way CMMs were designed and marketed.[10]

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7 K. Blaedel, "Error Reduction," in Robert J. Hocken, *Machine Tool Accuracy*, (Volume 5 of *Technology of Machine Tools*) Lawrence Livermore Laboratory, Report # UCRL-52960-5, October 1980, pp. 61-72.

8 Steven Phillips, et al., *Measurement Uncertainty Considerations for Coordinate Measurement Machines*, (NISTIR # 5170), April 1993, p. 7.

9 Error compensation is still regarded as the final step in the chain of CMM design strategies. See John A. Bosch (ed.) *Coordinate Measuring Machines and Systems*, (Marcel Dekker) 1995, pp. 279-300.

10 “Design Case Study: A Coordinate Measuring Machine,” in A.H. Slocum, *Precision Machine Design*, (Prentice-Hall) 1992, pp. 45-57.

3.4 NIST'S ROLE IN THE DEVELOPMENT AND DIFFUSION OF SEC

From approximately 1975 to 1985, NIST was engaged in a number of projects related to the development and demonstration of SEC technology. According to the scientists involved, "the fundamental mission of NIST's MEL was to push the state-of-the-art in measurement. The CMMs available to NIST at the time the project began were the very best but they were not good enough. Gage blocks, the conventional measurement technology at the time, were far more accurate than CMMs."[11] Yet, as described in Section 2.1.2 above, the conventional measurement technology was slow and inflexible. "[At the time], CMMs were not very well respected. ... We needed to improve their accuracy (our basic mission, after all, was (and is) to improve measurement accuracy) and SEC was one way to do it."[12]

A persistent theme in the interviews conducted with NIST staff and industry experts was the very conservative (technologically risk-averse) nature of the CMM industry. As discussed in Section 3.3, the reigning technological paradigm for improving the accuracy of CMMs was "error avoidance." At the time NIST initiated its SEC development efforts, CMM firms were unwilling to make the investments necessary to explore and demonstrate the feasibility of the SEC apporach to improving CMM accuracy.[13]

During the 1975 -1985 period, NIST research contributed the following to the development of SEC technology:

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[11] Personal communication with Robert J. Hocken (first project leader of NIST's SEC research efforts), 4/15/96. Simultaneous with much of the SEC rersearch, MEL's staff was also heavily involved in the development of a standard methodology for evaluating the performance of CMMs (*Methods for Performance Evaluation of Coordinate Measuring Machines,* ASME B89.1.12M-1985). Hocken recalls that once this standard was adopted most CMM producers had little choice but to adopt SEC. That is, the performance evaluation standard required a demonstration of accuracy that most CMM producers could only achieve by incorporating SEC technology. (In other industries performance standards have been shown to have significant economic impacts. See Albert Link, *Economic Impacts of NIST-Supported Standards for The U.S. Optical Fiber Industry,* (NIST) 1992.)

[12] Personal communication with Ralph Veale (SEC project participant), 4/16/96.

[13] Economic logic suggests that the reason for this lack of investment in SEC technology by private firms was rooted in the *ex ante* perception that the benefits of such research would not equal or exceed the costs or that if net benefits did accrue they could not be appropriated by the firms that made development investments.

- Demonstrated to industry the feasibility of three-dimensional software error correction for CMMs
- Implemented SEC on a relatively low cost CMM design
- Provided extensive explanation and consultation to producers and users of CMMs concerning the need for SEC and its practicability
- Demonstrated and explained to CMM producers the mathematics: how to construct the equations, how to solve the problem technically
- Demonstrated a systematic approach to taking and organizing the data for practical purposes and implemented a straight-forward approach to software implementation.

The results of these efforts were published in two technically important papers.[14]

A recent historical review of the scientific literature concerning software error compensation concluded that the most common current methods of SEC had their origin at NIST.[15] Industry representatives active in the market at the time of NIST's SEC efforts argue that NIST researchers demonstrated what could be done before it was economically feasible to do so commercially. Before SEC could take hold, the price of computer power had to drop to justify the manufacture of CMM using new designs.[16] Interviews with several of the original NIST researchers as well as numerous industry representatives uniformly describe a very conservative industry mind set that also had to be overcome in order for the acceptance and implementation of this new technology to proceed.

Beginning in the early 1970's, NIST's Manufacturing Engineering Laboratory, under the direction of Dr. John Simpson, undertook a project to computerize a relatively inexpensive CMM (a Moore-M5Z). Robert Hocken joined the project in 1975 and introduced an innovative

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[14] Robert J. Hocken, et al., "Three Dimensional Metrology," *CIRP Annals*, 1977; and G. Zhang, et al., "Error Compensation of Coordinate Measuring Machines," *CIRP Annals*, 1985. One indicator of the importance of these papers is their citation in commercial patents for SEC technology applications. Concerning the use of patent-based statistics for the evaluation of technology see, *Handbook of Quantitative Studies of Science and Technology*, A.F.J. Van Raan (ed.), (North-Holland) 1988.

[15] Robert J. Hocken, "Software Correction of Precision Machines," NIST Contract # NIST-60NANB2D1214, (Draft) July 1993

[16] John Hunt, "Software Hones CMM Accuracy," *Quality*, January 1996

conceptual approach to software error compensation. This initial work was published in 1977.[17] Over the course of some 10 years, a number of researchers participated in the project and made individual contributions to the implementation of the original Hocken concept.[18] In addition, industry advisory board representatives, including both Brown & Sharpe and Sheffield (now Giddings & Lewis), encouraged the development of SEC technology, seeing it as a means of competitive advantage with respect to foreign competitors, the Zeiss Company, of Germany, in particular.

Between 1982 and 1984, the NIST research team had succeeded in implementing and documenting three-dimensional error compensation on a commercial type machine, utilizing the Brown & Sharpe coordinate measuring machine "Validator" series.[19] These results were published by NIST researchers in 1985.[20] From NIST's perspective, the importance of the "Validator project" was that it introduced SEC technology into a widely used and relatively inexpensive CMM design.

Between the original Hocken-inspired efforts and the Validator projects, NIST researchers implemented SEC technology in a number of machine tool applications, including a Brown & Sharpe machining center (used in designing and manufacturing postage stamp perforation cylinders for the Bureau of Engraving & Printing) (1978); and a Hardinge turning center (1982).[21]

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[17] Robert J. Hocken, et al., "Three Dimensional Metrology," *CIRP Annals*, 1977

[18] Other project participants include: B. Borchardt, T. Charlton, J. Lazar, C. Reeve, P. Stein, R. Veale, and C. Zhang.

[19] There is some confusion concerning the timing of the implementation of full volumetric compensation and documentation of the Brown & Sharpe "Validator." NIST records indicate that the "Validator 200" was fully compensated in 1982. B&S representatives indicate that *full* volumetric error compensation was achieved later, in 1984, and that the "Validator 300" was the fully compensated model.

[20] G. Zhang, et al., "Error Compensation of Coordinate Measuring Machines," *CIRP Annals*, 1985.

[21] Some industry observers were skeptical of NIST's claims to be the original source of SEC technology, arguing that SEC actually had its origins in cutting and forming machine tool designs. As a means of assessing this issue we examined the "prior art" of patents granted to Sheffield (now Giddings & Lewis) and Brown & Sharpe for their software error compensation techniques. While we found a large number of prior art citations to machine tool companies and technologies, the prior art was for linear or two-dimensional compensation schemes, on the one hand, and mechanical approaches to compensation, on the other hand. The NIST innovation was in developing three-dimensional mathematical compensation schemes implemented in computer software. Since the professional papers of NIST researchers (Zhang, et.al., cited elsewhere in this report) were cited as part of the non-patent prior art references in the patent record, and because of the technical content of prior art patents, we conclude that NIST was indeed the original source of SEC technology.

Commercial introduction of “compensated” CMM’s began in the mid-1980s. U.S. industry representatives put the first commercial introductions in the 1984-1985 time frame, an estimated 5-10 years before U.S. firms would have introduced this technology without NIST’s efforts. Brown & Sharpe claims to have introduced an early compensated CMM (the “Validator-300”) in 1984 and another model (the “Excell”) in 1986. According to others, the Zeiss Company and the Sheffield Division of Bendix were the first to introduce full volumetric compensation on their CMM lines in 1985. The Sheffield and Brown & Sharpe implementations of SEC are clearly based on, or influenced by, the work performed at NIST in the preceding decade.[22]

For the purposes of estimating the economic impact of these development efforts, NIST’s efforts can be summarized, in terms of benefits to CMM producers (called first-order benefits) and to CMM users (called second-order benefits).

[22] Sheffield’s patents, “*Method for Calibrating a Coordinate Measuring Machine and the Like and System thereof*” (patent # 4819195; 4/4/89) and “*Method for Determining Position Within the Measuring Volume of a Coordinate Measuring Machine and System Thereof*” (patent # 4945501; 7/31/90), cite the professional papers of NIST researchers as prior art. Brown & Sharpe’s patent “*Method for Calibration of Coordinate Measuring Machine*” (patent # 4939678; 1990) cites Sheffield’s patent # 4819195 as prior art.

4. EVALUATION OF FIRST-ORDER ECONOMIC IMPACTS

4.1 SEC DEVELOPMENT COST AND FIRST-ORDER BENEFIT ESTIMATES

NIST researchers undertook their SEC-related research between 1975 and 1985. Over this 10 year period, a total of 7 work years were committed to the research project. In addition to this investment of time, there was a significant amount of equipment purchased.

Table 4.1-1 NIST SEC Research Costs[1]

Year	Work Years	Labor Costs	Equipment Costs
1975	0.5	$18.2K	$0.00
1976	0.5	$19.2K	$0.00
1977	0.5	$20.5K	$0.00
1978	0.5	$22.0K	$0.00
1979	0.5	$24.5K	$0.00
1980	0.5	$27.8K	$0.00
1981	1.0	$61.3K	$0.00
1982	1.0	$65.1K	$0.00
1983	1.0	$67.2K	$0.00
1984	1.0	$70.1K	$35.1

The first-order benefits quantified in this study relate to the feasibility research cost savings and related efficiency gains in production to CMM producers. We concluded from interviews with representatives from domestic CMM producers that in the absence of NIST's research in SEC

[1] When we asked NIST's staff in 1994 to reproduce the cost budget associated with this research program, no documentation was available. However, retrospectively NIST staff concur that the present value ($1994) of these 7 work years is $700,000, and the present value of the cost of the equipment is $50,000. NIST staff also concur that less labor was used in the early years of the project compared to the latter years. ("Software Error-Correction Measuring Machines," memorandum from Ralph Veale, Group Leader, Dimensional Metrology, March 14, 1994, provides an estimate of the resources NIST devoted to SEC development.) Therefore, for the purposes of constructing a time series of cost data it was assumed 0.5 work years were devoted to the research project in each year from 1975 through 1980, and then 1 work year in each year from 1981 through 1984. Similarly, we assumed that all equipment purchases occurred in 1984 (and this assumption will bias the impact results toward being conservative). To construct each data element in Table 4.1-1, $1994 estimates were deflated using the Consumer Price Index (1982-84=100). Thus, for example, $18.2K of labor costs in $1975 is equivalent to $50K of labor costs

technology they would have eventually undertaken the research cost to demonstrate SEC feasibility to remain competitive in the world market.[2] These costs were "saved" in the sense that NIST provided the technology to the domestic industry. In the absence of NIST, industry experts estimate that this research would have lagged NIST's research by between 5 (median response) and 6 (mean response) years. In other words, without NIST's investments, industry participants would not have begun to develop the relevant SEC technical information on their own until about 1981 (whereas NIST's research began in 1975). Industry experts predict that this research would have been undertaken independently by Brown & Sharpe and Sheffield (now Giddings & Lewis) owing to their market position and their knowledge that similar efforts were being undertaken by foreign competitors. Other domestic CMM companies would have benefited as the technical knowledge diffused, but were not in a financial position to underwrite such research.[3]

In an effort to create an "absent-NIST" scenario so as to quantify the feasibility research cost savings to the CMM industry, we assume that private sector research would have begun in 1981 and would have been completed in 1989 -- a 5 year lag in the state of knowledge. Those interviewed at Brown & Sharpe, Sheffield, and Starrett estimate that they would have expended collectively a total of 4 work years of effort between 1981 and 1989. In mid-1995, they valued a fully-burdened work year at $110,000 ($1994). (In telephone interviews, industry representatives were asked: *In the absence of NIST's research effort estimate the dollar value and timing of your firms investment to develop and test the feasibility of SEC.*) We believe that these absent-NIST estimates are overly conservative and obviously were constructed ex post in the absence of real-time experiential risk. They were forecast with hindsight and might well underestimate the risk of

in $1994. While the estimates in Table 4.1-1 represent the best institutional information available, it is important to emphasize that the conclusions reached in this study are dependent upon these cost assumptions.

2 Several interviews were conducted with each of the following individuals: James Beckwith (Brown & Sharpe) 10/28/94, 4/7/95, 4/19/96; John Bosch (formerly of Sheffield) 3/2/94, 6/30/95; Tom Charlton (Brown & Sharpe, formerly of NIST-MEL) 5/5/94, 7/22/94, 7/6/95; Bob Donaldson (Giddings & Lewis) 6/30/95, 7/7/95; Jack Hicks (DEA-North America) 6/15/94; Robert J. Hocken (University of North Carolina, formerly of NIST-MEL) 3/94, 5/94, 4/15/96 ; David Sloccum (Starrett Co.) 7/6/95; Ralph Veale (NIST-MEL) 4/94, 4/16/96; Donald Ward (Zeiss-North America) 6/94, 4/18/96; Art Wisler (Helmel Co.) 7/6/95.

3 After leaving NIST some SEC project personnel have been involved in the implementation of SEC for other domestic CMM producers.

the endeavor and hence the true cost to the industry. Nevertheless, these estimates are the best available.

Table 4.1-2 Industry SEC Research Cost Savings[4]

Year	Work Years	Nominal Labor Costs
1981	0.5	$33.7K
1982	0.5	$35.8K
1983	0.5	37.0K
1984	0.5	$38.6K
1985	0.5	$39.9K
1986	0.5	$40.7K
1987	0.5	$42.2K
1988	0.5	$43.9K

The data presented in Table 4.1-2 represent cost savings to the CMM industry. In addition, those CMM producers interviewed reported that they also realized efficiency gains in their production of CMMs. For the domestic CMM industry, the estimated efficiency gains ranged between 10 percent per year to 30 percent per year beginning in 1985, the year after NIST completed its feasibility research. (In telephone interviews, industry representatives were asked: *Holding machine accuracy constant, estimate the percent decrease in CMM production cost attributable to the introduction of SEC.)*   These gains in production efficiency for the entire CMM industry were estimated by the industry experts at $27M ($1994) per year (the sum of each producer's value of efficiency gain).

As shown in Table 4.1-3, the net productivity gains realized by the CMM industry are only for the years 1985 through 1988. NIST's SEC research was completed in 1984, and comparable research undertaken by the CMM industry would have been completed in 1989.

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4 It was assumed for the purposes of this analysis that the 4 work years of effort were evenly distriburted between 1981 and 1988, inclusive. To then construct each element in Table 4.1-2, $1994 estimates were deflated using the CPI. Thus, for example, $33.7K in $1981 equals $55k in $1994.

Table 4.1-3: Net CMM Industry Productivity Gains Resulting from NIST Research[5]

Year	Value of Nominal Productivity Gains
1985	$19.6M
1986	$20.0M
1987	$20.7M
1988	$21.5M

4.2 COMPARISON OF NIST RESEARCH COSTS TO CMM INDUSTRY BENEFITS

Table 4.2-1 shows the NIST research costs associated with the development and diffusion of SEC technology and the CMM industry benefits associated with using that technology. These CMM industry benefits are the sum of the industry's feasibility research cost savings (Table 4.1-2) and its net productivity gains (Table 4.1-3). Net benefits, by year, are the difference between the NIST costs and industry benefits series.

Table 4.2-1: Comparison of NIST Research Costs to CMM Industry Benefits

Year	NIST Labor & Equipment Costs	Industry Benefits	Total Net Benefits
1975	$18.2K		-$18.2K
1976	$19.2K		-$19.2K
1977	$20.5K		-$20.5K
1978	$22.0K		-$22.0K
1979	$24.5K		-$24.5K
1980	$27.8K		-$27.8K
1981	$61.3K	$33.7K	-$27.6K
1982	$65.1K	$35.8K	-$29.3K
1983	$67.2K	$37.0K	-$30.2K
1984	$105.2K	$38.6K	-$66.6K
1985		$19.64M	$19.64M
1986		$20.04M	$20.04M
1987		$20.74M	$20.74M
1988		$21.54M	$21.54M

[5] These data elements were constructed by deflating $27M ($1994) by the CPI.

5. ESTIMATION OF FIRST-ORDER ECONOMIC IMPACTS OF NIST'S RESEARCH ON SEC TECHNOLOGY

The cost and benefit data summarized in Table 4.2-1 are the basis for the evaluation analysis presented in this section. Two evaluation metrics were considered: a benefit-to-cost ratio and a social rate of return estimation[1]. Both metrics have merit; however, the social rate of return is employed in order to facilitate a comparison of these results with the results from previous NIST evaluation studies and studies of industrial innovations.

By definition, the social rate of return is the value of the discount rate i that equates the net present value (NPV) of a benefit stream to zero. The net present value of a project equals:

$$NPV = [(B_0-C_0)/(1+i)^0] + ... + [(B_n-C_n)/(1+i)^n] = 0$$

where (B_t-C_t) represents net benefits and the subscripts index time periods.

Based on the total net benefits data in Table 4.2-1, the calculated value of i for which NPV=0 is 0.987, implying an social rate of return for NIST's research in SEC technology of 99 percent. It should be noted that when NPV=0, the ratio of benefits-to-costs, B/C, equal 1. To illustrate, NPV can be rewritten as:

$$NPV = [\Sigma_{t=0 \text{ to } n} B_t/(1+r)^t] - [\Sigma_{t=0 \text{ to } n} C_t/(1+r)^t]$$

where r is the discount rate used to deflate future benefit and cost estimated to present value terms. When NPV=0, then it follows that:

$$[\Sigma_{t=0 \text{ to } n} B_t/(1+r)^t] = [\Sigma_{t=0 \text{ to } n} C_t/(1+r)^t]$$

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1 The social rate of return is an application of the "internal rate of return" calculation used for decades in investment planning by the business community. See Gregory Tassey, *Rates of Return from Investments in Technology Infrastructure,* draft planning report 96-3, NIST, May 1996

or that the present value of benefits equals the present value of costs, or B/C=1. The social rate of return estimate of 99 percent means that 0.99 is the value of the discount rate that equates the present value of benefits to the present value of costs.

As is well known, economists and policy makers would generally conclude if 99 percent is above NIST's hurdle rate or generally accepted expected rate of return for research projects such as the SEC project, then the project was worthwhile.[2]

Under alternative sets of assumptions, one could calculate from the data in Table 4.2-1, an adjusted rate of return. For example, if all NIST costs were referenced to 1975 using a discount rate of 8.96 percent, total investments in this hypothetical project are $206,335.[3] If all benefits are referenced to 1988 using the same rate, total benefits from this hypothetical project are $93,569,320. Thus, one could think of this project as one where an initial investment of $206,335 generated, after 13 years, benefits to industry equaling $93,569,320.

One could calculate the annual compounded rate of return that corresponds to an initial investment of $206,335 in 1975 growing to $93,569,320 by the end of 1988 due to reinvestment of proceeds from the initial investment. Such a compounded rate of return, x, equals approximately 60 percent based on the following relationship:

$$\$206{,}335(1+x)^{13} = \$93{,}569{,}320$$

In other words, $206,355 invested in 1975, earning 60 percent compounded, would grow to $93,569,320.

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2 For government investment projects the minimum rate of return is officially designated by the Office of Management and Budget (OMB) to be the market rate of interest which the government pays to the public in order to raise the necessary funds for investment projects. OMB Circular No. A-94 provides discount rates for different evaluation time periods. See, Gregory Tassey, *Rates of Return from Investments in Technology Infrastructure,* draft planning report 96-3, NIST, May 1996.

3 This discount rate equals the average yield on 3-year Treasury bonds in 1994, as reported in the *Economic Report of the President, 1995*. The year 1988 was selected because it is the year for which all benefits end. However, there is no methodological reason for the selection of such a year or for even for the use of the 30-year Treasury bond yield. This calculation is intended only to illustrate alternative interpretations for the data in Table 4.2-1, as opposed to the implementation of an alternative evaluation metric.

One should not expect this adjusted rate of return to equal the previously calculated internal rate of return. Each was calculated under different assumptions. And, if the assumptions change, both calculated rates will change.

While the adjusted rate of return has a commonplace interpretation, the assumptions underlying it do not conform to the realities of the data in Table 4.2-1, or to the pattern of investments in research at NIST and the trend in realized benefits by industry. That is, the benefits from NIST's SEC research project were not realized gradually over the course of the project and reinvested. Rather the benefits accrued to industry largely after the NIST project was completed. Only then were the benefits of the NIST project incorporated by industry. Hence, the social rate of return estimate of 99 percent is the accepted evaluation metric and should be interpreted, in comparison to NIST's hurdle rate, in order to conclude whether or not a project was worthwhile.

Although only first-order economic benefits were estimated in this study, it was the consensus opinion of all industry experts that the second-order benefits realized by users of SEC-compensated CMMs are significantly greater in value. Thus, the quantitative findings presented in this report should be viewed as a lower-end value of the net benefits to industry resulting from NIST's research in SEC technology.

The second-order benefits of software compensated CMMs will accrue to CMM users. Based on the information provided in Section 2.1 (Table 2.1-4 and Table 2.1-5), we expect the benefits of NIST's SEC impacts to be felt by large and small manufacturers alike and to be concentrated in the Industrial Machinery & Equipment and the Transportation Equipment industries. Based on discussions with CMM producers, the benefits to users will take to form of inspection cost savings, reduced scrape rates and related inventory costs savings, and lower CMM maintenance costs.

Finally, the first and second order benefits of SEC technology are but examples of the total benefits that have likely resulted from NIST's focus on dimensional metrology. For example, it has been suggested that the implementation of SEC technology in cutting and forming machine tools has begun and that this implementation represents as significant a change for that segment of the machine tool industry as it has for the CMM industry.[4] The CMM performance evaluation standard, mentioned briefly in Section 3.3, seems to have played an important role in the diffusion of CMMs by lowering the transaction costs associated with the purchase of these relatively expensive and complex machines and reducing the information asymmetry between sellers and buyers of CMMs. In addition, MEL's recent Interim Test Device project already appears to be significantly reducing CMM users' maintenance and calibration costs. While methodological difficulties prevent the estimation of the overall social benefits of NIST's ongoing dimensional metrology research program, we suspect the sum of the economic impacts of a broader basket of representative CMM-related cases would be at least as impressive as the returns to NIST's SEC research assessed in this report.

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[4] Jun Ni, "Coordinate Measuring Machines," in John A. Bosch (ed.) *Coordinate Measuring Machine Systems,* p. 40 (draft manuscript) 1994.